(19) Europäisches Patentamt
European Patent Office
Office européen des brevets

(11) EP 0 849 082 A2

(12) EUROPEAN PATENT APPLICATION

(43) Date of publication:
24.06.1998 Bulletin 1998/26

(51) Int. Cl.[6]: **B41J 2/06**, B41J 2/14, B41J 2/16

(21) Application number: 97122537.0

(22) Date of filing: 19.12.1997

(84) Designated Contracting States:
AT BE CH DE DK ES FI FR GB GR IE IT LI LU MC NL PT SE
Designated Extension States:
AL LT LV MK RO SI

(30) Priority: 20.12.1996 JP 342213/96
16.10.1997 JP 284127/97

(71) Applicant:
SEIKO EPSON CORPORATION
Tokyo 163 (JP)

(72) Inventors:
- Sato, Kazuhiko
Suwa-shi, Nagano-ken 392 (JP)
- Maruyama, Hiroyuki
Suwa-shi, Nagano-ken 392 (JP)
- Fujii, Masahiro
Suwa-shi, Nagano-ken 392 (JP)
- Hagata, Tadaaki
Suwa-shi, Nagano-ken 392 (JP)
- Kitahara, Koji
Suwa-shi, Nagano-ken 392 (JP)
- Mukaiyama, Keiichi
Suwa-shi, Nagano-ken 392 (JP)

(74) Representative:
Hoffmann, Eckart, Dipl.-Ing.
Patentanwalt,
Bahnhofstrasse 103
82166 Gräfelfing (DE)

(54) Electrostatic actuator and method of manufacturing it

(57) An electrostatic actuator comprising opposing electrode members displaced relatively by an electrostatic force is provided with improved durability so that electrostatic attraction between the opposing electrode members does not drop and the opposing electrode members do not stick together. Hydrophobic films (22) and (23) of hexamethyldisilazane (HMDS) are formed on the surface of a segment electrode (19) and the bottom surface of a diaphragm (common electrode) (6) of electrostatic actuator wherein the diaphragm forms a wall of an ink chamber 7 in a ink jet head 1. HMDS molecules are smaller than PFDA molecules, and a uniform, variation-free hydrophobic film can therefore be formed even when the gap between the two electrodes is narrow. Durability and film stability of hydrophobic films are also high. An electrostatic actuator with high durability and operating stability can thus be achieved.

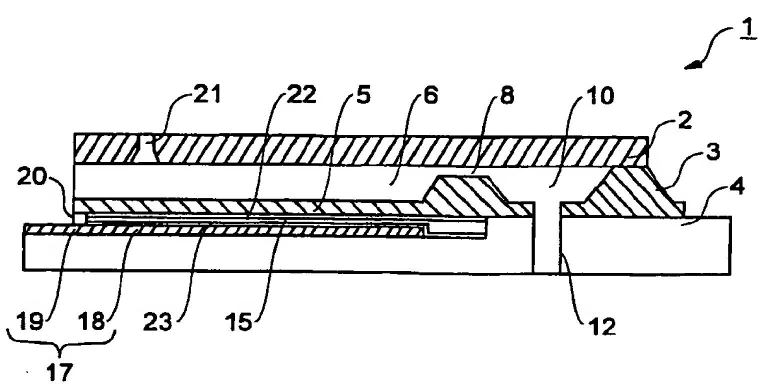

FIG. 2

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Description

The present invention relates to an electrostatic actuator using an electrostatic force for moving one of two electrode members, which oppose each other via a gap, relative to the other wherein the electrostatic force is generated by applying a voltage between two electrodes formed by or attached to the two electrode members. The invention also relates to a method of manufacturing such electrostatic actuator. More specifically, the present invention relates to a method for forming a hydrophobic film on at least one of the two electrode members of the electrostatic actuator.

Various types of actuator with a microstructure formed by using semiconductor microprocessing technologies are widely used in ink jet heads for ink jet printers. These types of actuator use different drive principles, one of which is an electrostatic drive, i.e., use of an electrostatic force for creating a relative motion between two electrode members disposed opposite to each other with a gap in between. Ink jet heads that use electrostatic force to eject ink drops are disclosed in e.g. JP-A-5-50601/1993, 6-70882/1994 and EP-A-0 580 283.

This type of ink jet head has, in communication with each of a plurality of nozzles, a respective ink chamber whose bottom is formed as an elastically deformable diaphragm. The diaphragm is disposed opposite a substrate with a certain gap therebetween. Mutually opposing electrodes are disposed on/by the diaphragm and the substrate, respectively, and the space between the electrodes is sealed. In this case, the diaphragm and the substrate form the two opposing electrode members of an electrostatic actuator. When a voltage is applied to the electrodes, the electrostatic force created in the gap causes the bottom of the ink chamber, i.e., the diaphragm, to vibrate as a result of the electrostatic attraction to and repulsion from the substrate. The change in the internal pressure of the ink chamber resulting from this vibration causes one or more ink drops to be ejected from the nozzle. A so-called "ink-on-demand" drive method wherein ink drops are ejected only when needed for recording can thus be achieved by controlling the voltage applied to the electrodes of the respective electrostatic actuator.

If moisture gets on the surfaces of the opposing electrode members (the surfaces that face each other, also referred to as the "opposing surfaces" hereinafter) while the ink jet head is being driven by repeatedly applying a voltage to the electrodes, the charge of polar molecules may cause a drop in electrostatic attraction or repulsion properties. If polar molecules adhering to the opposing surfaces form hydrogen bonds, the bottom of the ink chamber (the diaphragm) may stick to the substrate and can become inoperable.

One possibility of avoiding these problems is to treat those opposing surfaces so that they are made hydrophobic. One means of achieving this is to coat these surfaces with an oriented monolayer of perfluordecanoic acid (PFDA).

An electrostatic actuator which is used for moving micro mirrors and in which PFDA is used for hydrophobic treatment is disclosed, for example, in JP-A-7-13007/1995 and corresponding US-A-5,331,454. These documents teach a method of preventing the opposing surfaces of the actuator from sticking together when driven by forming an oriented monolayer of PFDA on these surfaces.

Hydrophobic processing using PFDA, however, leaves the following problems to be solved. First, the durability of the PFDA layers formed by simply depositing PFDA on the opposing surfaces of electrode members movable relative to each other is insufficient. As a result, the PFDA layer separates from the surface of the underlying electrode member as a result of the electrostatic field repeatedly generated between the electrode members to repeatedly displace them relative to each other. These separated layer particles then tend to clump together, creating foreign matter inhibiting relative displacement between the electrode members. When such foreign matter is formed, the danger of the electrostatic actuator becoming inoperable arises.

The gap between the opposing electrode members in an electrostatic actuator is preferably as narrow as possible in order to generate a sufficiently high electrostatic force at a relatively low voltage. It is also preferable to minimize this gap as much as possible in order to reduce the size and achieving a higher density arrangement of electrostatic actuators. PFDA molecules are relatively large, however, and if the gap becomes too narrow, it is not possible to deposit PFDA on the opposing surfaces separated by this narrow gap.

A paper distributed in November 1990 and titled "Surface Forces in Micromachined Structures" by P.R. Scheeper et al. of the University of Twente, The Netherlands discusses the use of a hydrophobic film to prevent relatively movable members in a micromachined structure from sticking together. According to this paper, HMDS (hexamethydisilazane) films have been applied to diaphragms and beams as movable members made form PECVD silicon nitride and proven to substantially decrease the likelihood of the movable members to stick to the substrate.

An object of the present invention is to provide an electrostatic actuator having a durable hydrophobic film, and to provide a manufacturing method therefor.

A further object of the present invention is to provide an electrostatic actuator comprising a hydrophobic film that can be deposited on the surfaces of opposing members even when the gap between the opposing members adapted to be displaced relative to each other by an electrostatic force is narrow, and to provide a manufacturing method therefor.

This object is achieved with an electrostatic actuator as claimed in claim 1 and a method as claimed in claim 7, respectively. Preferred embodiments of the

invention are subject-matter of the dependent claims.

In accordance with the present invention, a hydrophobic film of an organosilicate compound having a hydrophobic functional group and the ability to react with a hydroxyl group, in particular, a compound having the general formula R_3SiX, wherein R represents an alkyl group and X represents either a halogen or an amino group or silylated amine, is formed on one or both of the opposing surfaces of the electrostatic actuator and the gap between the two opposing electrode members is sealed airtight. This hydrophobic film is more durable than a hydrophobic film of PFDA. Furthermore, molecules of such compound are small and can, therefore, be deposited on one or both of the opposing surfaces even when the gap between them is narrow.

The inventors of the present invention investigated the durability of an HMDS (hexamethydisilazane) hydrophobic film (HMDS film) formed on the opposing surfaces when the HMDS film was exposed to the air immediately after deposition. As shown in Fig. 7, it was found that the durability drops sharply immediately after exposure, and then settles to a specific level after several minutes. If then left exposed for several days, the durability gradually recovers. More specifically, when the gap between the opposing electrode members is sealed during period B in Fig. 7, and charging/discharging of the capacitor formed by the opposing electrode members is repeated four to five million times, a gelatinous substance (foreign matter) occurs in the gap between the opposing electrode members, and operating the actuator becomes difficult. The earlier this gap between the opposing electrode members is sealed, however, the longer it takes for this gelatinous substance to appear (period A). More specifically, the greater the concentration of HMDS in the gap, the more difficult the occurrence of this gelatinous substance becomes. On the other hand, creation of this gelatinous substance also becomes more difficult when the time until the gap is sealed with respect to the surrounding air exceeds a specific time (period C).

This unique phenomenon suggests that a surplus of HMDS in the gap facilitates the occurrence of this gelatinous substance as the charging/discharging of the electrostatic actuator is repeated, but that sealing an extreme surplus of HMDS in the gap conversely suppresses the occurrence of the gelatinous substance. In addition, if the delay until the gap is sealed exceeds a certain time, excess HMDS is eliminated by hydrolysis, and the surplus HMDS that is a source of foreign matter is thought to be eliminated.

These experimental results show that a durable hydrophobic film can be obtained after forming an HMDS film on the opposing surfaces by either (1) sealing the gap in which the HMDS is deposited while the HMDS concentration in the gap is still above a particular level, or (2) sealing said gap after leaving it exposed to the air for a plurality of days.

The present inventors conducted a further study with electrostatic actuators manufactured by method (1) above, that is, sealing the gap to air while the HMDS concentration therein was above a particular level. These studies confirmed that the durability of the hydrophobic film is improved to a level suitable for practical use if the gap is sealed with respect to the surrounding air while the HMDS concentration is 0.3% or greater. A hydrophobic film of sufficient practical durability can also be achieved when the gap is sealed while the HMDS concentration is 0.8% or greater.

It was also confirmed that the sealing step can be performed at room temperature and atmospheric pressure.

The deposition step can also be achieved by simply exposing the opposing electrode members to an atmosphere of gasified HMDS at atmospheric pressure until a predefined concentration is obtained. After an HMDS film is thus formed, the gap between the opposing electrode members is sealed while they are kept in the HMDS atmosphere. By sealing the gap while in the HMDS atmosphere, the HMDS concentration in the gap can be reliably maintained above a specific level.

In further studies using electrostatic actuators manufactured by method (2) above, that is, sealing the gap after exposing the opposing electrode members to air for a plurality of days, it was found that moisture is preferably actively supplied during the exposure period. More specifically, leaving the opposing electrode members exposed to a moisture-rich atmosphere promotes HMDS hydrolysis, thereby more quickly eliminating the surplus HMDS that contributes to the production of foreign matter, and forming a stable hydrophobic film.

It should be noted that whether the gap between the opposing electrode members is sealed immediately or after a period of days in accordance with methods (1) or (2) above, a pretreatment step for reducing the moisture content in the gap preferably precedes the deposition step. More specifically, the manufacturing method for an electrostatic actuator according to the present invention preferably comprises a drying step for reducing the moisture content in the gap before the deposition step. This drying step helps stabilizing the HMDS deposition, and can avoid variations in the HMDS deposition during the sealing step.

Further objects and advantages achieved by the present invention will be more fully understood from the following description of preferred embodiments with reference to the drawings.

Fig. 1 is an exploded perspective partial view of an ink jet head to which the present invention is applied.

Fig. 2 is a lateral cross sectional view of the ink jet head shown in Fig. 1.

Fig. 3 is a plan view of the ink jet head shown in Fig. 1.

Fig. 4 is a enlarged partial cross sectional view of the ink jet head shown in Fig. 1 along line IV-IV in Fig. 3.

Fig. 5 is a simplified flow chart of a manufacturing method for an ink jet head 1 as shown in Fig. 1.

Fig. 6 is an illustration of a hexamethyldisilazane hydrophobic film formed by the manufacturing method of the invention.

Fig. 7 is a graph of the relationship between the durability of a hydrophobic film and the delay until gap sealing when the gap is exposed to air immediately after hydrophobic film formation.

Fig. 8 is a graph of the relationship between the durability of a hydrophobic film of hexamethyldisilazane and the hexamethyldisilazane concentration in the gap obtained when the gap is sealed after removal from the HMDS deposition chamber within the period of the downward trending curve in Fig. 7.

Fig. 9 is a simplified flow chart of a manufacturing method according to an alternative embodiment of the present invention for an ink jet head 1 as shown in Fig. 1.

Fig. 10 is a plan view of the seal area of the gap between opposing electrode members in the ink jet head shown in Fig. 1.

Fig. 11 is a plan view of the seal area of the gap between opposing electrode members of an ink jet head according to an alternative embodiment of the invention.

Preferred embodiments of the electrostatic actuator according to the present invention are described below as applied to an ink jet head forming one field of application of such actuator.

Basic configuration

Fig. 1 is an exploded perspective partial view of an ink jet head 1 which employs electrostatically driven actuators for ink drop ejection. The ink jet head in this embodiment is a face nozzle type ink jet head wherein ink drops are ejected from ink nozzles formed on the top surface of the ink jet head. The ink jet head 1 comprises a three-layer structure with a nozzle plate 2 on the top, a glass substrate 4 at the bottom and an intermediate plate 3 in between.

The material for the intermediate plate 3 is not critical to the present invention but preferably it is made from a silicon substrate. A recess 11 and a plurality of pairs of a recess 7 and a narrow channel 9 are formed by etching in the surface of the intermediate plate 3. The bottom of intermediate plate 3 is smoothed by mirror polishing.

The nozzle plate 2 is also preferably made from a silicon substrate. When the nozzle plate 2 is bonded to the top side of intermediate plate 3, recess 11, recesses 7 and recesses 9 are covered, and recess 11 becomes an ink reservoir 10, recesses 7 become separate ink chambers 6 and channels 9 become ink supply openings 8. Each ink chamber 6 is connected at its back side via a respective one of ink supply openings 8 to ink reservoir 10 from which ink is supplied to each ink chamber 6. A plurality of nozzles openings or simply nozzles 21, each opening into a corresponding one of ink chambers 6, is formed through nozzle plate 2.

The glass substrate 4 bonded to the bottom side of intermediate plate 3 is preferably a borosilicate glass substrate having a thermal expansion coefficient close to that of silicon. A plurality of recesses 16 is formed in the surface of glass substrate 4 facing intermediate plate 3. Each recess 16 is registered with one of the ink chambers 6 so that, in the bonded state, a respective vibration chamber or actuator cavity 15 is formed between the bottom of each ink chamber and the bottom of the corresponding recess 16.

A hole 12a is disposed in the bottom of recess 11, and a corresponding hole 12b is formed through glass substrate 4 such that after glass substrate 4 is bonded to intermediate plate 3, an ink supply hole 12 is formed from holes 12a and 12b. A supply tube not shown in the figures is connected between ink supply hole 12 and an ink tank, which also is not shown in the figures, for supplying ink to ink reservoir 10. The ink supplied through ink supply hole 12 is supplied via the individual ink supply openings 8 to the separate ink chambers 6.

An electrostatic actuator is provided for each of the ink chambers. Its purpose is to temporarily increase the pressure inside the respective ink chamber thereby to eject an ink droplet through the corresponding nozzle. The electrostatic actuator comprises two electrode members opposing each other via a small gap. A first electrode member is formed as a deflectable diaphragm 5. In the ink jet head described above, the bottom of the ink chamber forms the diaphragm 5. The second electrode member is formed by the bottom of the corresponding recess 16 on which an electrode is provided. In the present embodiment, the intermediate plate 3 is electrically conductive so the diaphragm can also be called an electrode. Since the diaphragms of all ink chambers 6 are electrically connected to each other, the diaphragm will also be referred to as the "common electrode" and the electrode on the bottom of recess 16 as the "segment electrode" of the actuator. The segment electrode 18 is part of a respective electrode part 17 comprising this segment electrode 18 made from ITO, and a terminal portion 19.

When glass substrate 4 is bonded to intermediate plate 3, each diaphragm 5 (i.e., bottom of ink chamber 6) and the corresponding segment electrode 18 are separated by an extremely narrow gap within the respective actuator cavity 15. This actuator cavity 15 is sealed by a sealant 20 disposed between intermediate plate 3 and glass substrate 4. Note that with the segment electrode on the bottom of the recess 16 the actuator cavity is substantially identical with the gap between the two electrode members, i.e., the diaphragm 5 and the segment electrode 18.

Diaphragm 5 is a thin-wall member that is elastically deformable in the direction perpendicular to its surface, that is, in the vertical direction as seen in Fig. 2. The bottom surface 51 of the diaphragm 5 is coated with a hydrophobic film 22 of hexamethyldisilazane (HMDS). Another hydrophobic film 23 of hexamethyldisilazane (HMDS) is formed on the top surface of the segment electrode 18. Films 22 and 23 will be referred to as HMDS films hereinafter.

A voltage applying means 25 is connected to apply a drive voltage across each diaphragm 5 and the associated segment electrode 18. One of a plurality of second outputs of voltage applying means 25 is connected to the terminal portion 19 of a respective electrode part 17, and another output is connected to a common electrode terminal 26 formed on intermediate plate 3. In order to decrease the electrical resistance between common electrode terminal 26 and each diaphragm 5, a thin film of gold or other conductive material may be formed on one surface of intermediate plate 3 by means of vapor deposition, sputtering, or other method. Anodic bonding is used for connecting intermediate plate 3 and glass substrate 4 in the present embodiment, and such conductive film is therefore formed on the surface of intermediate plate 3 on which the ink flow paths are formed. Such conductive film may also be employed when an insulating material is used for the intermediate substrate.

When a drive voltage is applied from voltage applying means 25 across the opposing electrodes 5 and 18 of an electrostatic actuator in ink jet head 1 thus comprised, a Coulomb force is produced by the charge accumulating on the opposing electrodes, which causes diaphragm 5 to be deflected from its initial or stationary position toward segment electrode 18 thereby increasing the volume of the respective ink chamber 6. When the drive voltage is then removed (i.e., the common electrode and the segment electrode are shorted) the charge stored on the opposing electrodes is discharged, and diaphragm 5 returns to its stationary position by its inherent elastic restoring force, thus rapidly reducing the volume of the ink chamber 6. The resulting pressure change within the ink chamber causes part of the ink contained therein to be ejected through the associated nozzle 21 onto a recording medium (not shown).

Note that the ink preferably used by the ink jet head 1 explained above is prepared by dissolving or dispersing a dye or pigment with a surface active agent such as ethylene glycol in water, alcohol, toluene or other primary solvent. A hot melt ink can also be used if a heater is further provided for ink jet head 1.

Manufacturing method

A preferred method of manufacturing ink jet head 1 with the electrostatic actuators according to the present invention is described below with reference to Fig. 5.

As shown in Fig. 5, this manufacturing process starts by processing intermediate plate 3, nozzle plate 2 and glass substrate 4 wafers (step ST1). The three wafers are then assembled (bonded) in step ST2 to form the ink jet head. It should be noted that at this time the HMDS film is not formed yet, neither on the bottom surface 51 of the diaphragms 5 nor the surface of segment electrodes 18. Furthermore, the actuator cavities 15 are not sealed yet.

The ink jet head 1 is then preprocessed by a drying process in step ST3 to eliminate or reduce, to the lowest possible level, moisture on the opposing surfaces on which the HMDS film is to be formed. This can be accomplished by, for example, exposing ink jet head 1 in a processing chamber to a dry air stream. This preprocessing step helps stabilizing the HMDS deposition state by eliminating or reducing excess moisture on the bottom surface 51 of diaphragms 5 and the surface of segment electrodes 18, thereby avoiding variations in the deposition state of HMDS in the next process step.

This preprocessing step can be also be accomplished by a vacuum heating process in which the ink jet head is heated in a vacuum chamber, a process in which the ink jet head is placed in a processing chamber which is alternately switched between vacuum and nitrogen environments, or a process combining these methods.

HMDS films 22 and 23 are then deposited on the bottom surface 51 of diaphragms 5 and the surface of segment electrodes 18 in the HMDS deposition step (ST4). This can be accomplished by, for example, placing a container of HMDS in the preprocessing chamber, stopping the supply of dry air, returning the chamber to room temperature, normal humidity (45%-85% relative humidity) and atmospheric pressure, and maintaining this environment until the actuator cavities 15 (actually formed by the gap between the diaphragm and the segment electrode) are sufficiently penetrated by HMDS diffusion. In a test, sufficient HMDS diffusion required approximately twenty hours in the preferred embodiment of the invention with an HMDS concentration of approximately 0.3% or greater in the processing chamber. This deposition process results in hydrophobic HMDS films 22 and 23 being deposited on the bottom surface 51 of diaphragms 5 and the surface of segment electrodes 18.

The molecular bonding of the HMDS layers 22a and

23a formed on the bottom surface 51 of a silicon diaphragm 5 and an ITO segment electrode 18 is illustrated in Fig. 6 showing that an OH group is replaced by an $OSi(CH_3)_3$ group on each surface.

Without removing the ink jet head 1 from the processing chamber, the actuator cavities 15 are sealed airtight in the sealing step (ST5). The concentration of HMDS in the sealed actuator cavities 15 at this time is approximately 0.3% or greater.

Fig. 7 is a graph of the relationship between the durability of HMDS films 22 and 23 and the exposure time (the time until the actuator cavities are sealed) when the ink jet head is exposed to air immediately after formation of the HMDS films 22 and 23. It should be noted that the curve shown in Fig. 7 was obtained using an HMDS concentration inside the processing chamber of 0.8% or greater during the sealing process. Note further, that the durability was measured as the number of deflection cycles of diaphragm 5 the films withstood without separating.

As shown by the downward trending curve in period A in Fig. 7, the durability of HMDS films 22 and 23 drops sharply immediately after removal from the processing chamber, when the ink jet head 1 is removed from the processing chamber and HMDS films 22 and 23 are exposed to air before the actuator cavities 15 are sealed. Durability then stabilizes at a certain level after a some minutes, and remains stable at substantially this level throughout period B. Durability then gradually recovers after a plurality of days as indicated by the upward trending curve in period C. It should be further noted, however, that the durability of HMDS films 22 and 23 in period C remains lower than that immediately after film formation in period A.

In the manufacturing method of the present invention, the actuator cavities 15 are sealed while the HMDS concentration therein is approximately 0.3% or greater. The actuator cavities 15 are therefore essentially sealed immediately after forming the HMDS films 22 and 23, that is, in the downward trending period A of Fig. 7. The durability of HMDS films 22 and 23 formed on the surface of diaphragms 5 and the surface of segment electrodes 18 is therefore substantially the same as the film durability immediately after the HMDS films 22 and 23 are formed.

Fig. 8 is a graph of the relationship between the durability of HMDS films 22 and 23 and the HMDS concentration in the actuator cavities 15 when the actuator cavities 15 are sealed within the downward trending period A shown in Fig. 7. As will be seen from this graph, because ink jet head 1 is sealed so that the HMDS concentration in actuator cavities 15 is 0.3% or greater, the durability of HMDS films 22 and 23 is a minimum of approximately 20 million cycles. This means that HMDS films with a durability comparable to or greater than that obtained when actuator cavities 15 are sealed a period of days after forming the HMDS films 22 and 23 can be obtained. Furthermore, as also shown in Fig. 8, HMDS films 22 and 23 with durability sufficient to withstand 100 million cycles or more can be obtained when the HMDS concentration in actuator cavities 15 is approximately 0.4% or greater.

Note, further, that the durability of HMDS films 22 and 23 continues to rise as the HMDS concentration in actuator cavities 15 increases until at an HMDS concentration of approximately 0.8% the durability is saturated at approximately five billion cycles.

Therefore, to compensate for control variations in the HMDS concentration in the processing chamber, the HMDS concentration in the processing chamber is preferably set to approximately 1.0% to 1.1%, and actuator cavities 15 are preferably sealed while in the processing chamber. As also described above, it is not necessary to wait a period of days after HMDS film formation in order to assure sufficient durability of the HMDS films 22 and 23. As a result, the method of the present invention has the further advantage of allowing to manufacture electrostatic actuators in a short period of time suitable for mass production.

Note, further, that the sealing process can also be accomplished after removing ink jet head 1 from the processing chamber. However, because the durability of HMDS films 22 and 23 drops rapidly when ink jet head 1 is removed from the processing chamber as shown in Fig. 7, it is necessary to seal the actuator cavities of ink jet head 1 within approximately the first three minutes immediately after removal from the processing chamber assuming the parameters shown in Fig. 7.

It must be further noted that during the HMDS deposition process shown as step ST4 in Fig. 5 HMDS may enter through nozzles 21 and/or ink supply hole 12 and form a HMDS film on surfaces of the ink flow path formed by intermediate plate 3 and nozzle plate 2. The resulting hydrophobicity of those surfaces degrades the ability of the ink jet head to expel air bubbles from the ink path. This problem can be resolved, however, by removing the HMDS film from the ink path surfaces by means of an RCA cleaning process (cleaning with a solution of ammonia and hydrogen peroxide) following the sealing process of step ST5.

Manufacturing method according to an alternative embodiment

The manufacturing method of the present invention described above seals the actuator cavity 15 while the HMDS concentration therein is at a particular level using the characteristics of period A in Fig. 7. Sealing the actuator cavity while the HMDS concentration is maintained at such particular level can be difficult, however, depending upon the configuration of the electrostatic actuator (ink jet head) and manufacturing equipment-related considerations. In such cases the durability can be improved by actively utilizing the characteristics shown in period C of Fig. 7 after the deposition process. A manufacturing method according to a

alternative embodiment of the invention based on this is described next with reference to the flow chart in Fig. 9. Note that identical steps in the flow charts in Fig. 5 and Fig. 9 are identified by like reference numerals, and further description thereof is thus omitted below.

Steps ST1 and ST2 are the same as those in Fig. 5, resulting in an assembled ink jet head in which a HMDS film is not formed yet, neither on the surface of diaphragms 5 nor on segment electrodes 18. The same process is also used in step ST3 to eliminate or reduce moisture from those surfaces.

In the HMDS deposition process of step ST4, however, HMDS can be deposited on the bottom surface 51 of diaphragms 5 and the surface of segment electrodes 18 using either a gas or liquid phase process. A gas phase process can be accomplished by a method depositing HMDS at atmospheric pressure or by a vacuum deposition method. While the preceding embodiment deposits HMDS at atmospheric air pressure, the present embodiment does not seal the actuator cavity immediately after HMDS deposition, and is therefore not limited to depositing HMDS at atmospheric (normal) pressure. For example, a HMDS film can be formed on the bottom surface 51 of diaphragms 5 and segment electrodes 18 by maintaining ink jet head 1 in an HMDS atmosphere at between 20°C and 200°C for a period between approximately 5 and 150 minutes at a vacuum of 10 Torr (1.3 kPa) or greater.

A liquid phase method deposits HMDS by immersing the ink jet head in HMDS. This method relies upon a capillary action for HMDS to enter the actuator cavities 15 and be deposited on the bottom surface 51 of diaphragms 5 and segment electrodes 18. In an exemplary embodiment of this method, ink jet head 1 and HMDS are held at room temperature, and ink jet head 1 is immersed in an HMDS solution for five minutes or longer. Excess HMDS is then removed from actuator cavity by exposing the ink jet head to an atmosphere of 20°C to 200°C. This method offers the advantage of depositing HMDS in a short time.

Post-processing steps (ST4b) include a moisture imparting process and an exposure process as explained below. Note that these methods can be used either independently or in combination.

A moisture imparting process removes excess HMDS from the HMDS film by supplying moisture to promote hydrolysis. Supplying moisture to the HMDS film suppresses the occurrence of foreign matter as a result of HMDS film aging, and has been confirmed to improve the stability of the HMDS film. In an exemplary embodiment of this process, the ink jet head is exposed after HMDS deposition to an atmosphere between 20°C and 200°C with 20% to 100% relative humidity. This moisture imparting process can be initiated after the HMDS deposition process is completed, or while the HMDS deposition process is still in progress. If moisture imparting is initiated while the HMDS deposition process is still in progress, the ink jet head is placed in an atmosphere of only HMDS at the beginning of HMDS deposition, and moisture is then added to the HMDS atmosphere at some point during the HMDS deposition.

In the exposure process, the ink jet head is placed and left after HMDS deposition in an atmosphere between 20°C and 200°C at a relative humidity of 45% to 85%, preferably, about 60%, for a period between a day or two to approximately one week. This process promotes stabilization of HMDS bonding, suppresses the occurrence of foreign matter as a result of HMDS film aging, and improves film stability.

The actuator cavities 15 are sealed (ST5) after these processes are completed to complete the manufacturing process.

Actuator cavity sealing structure in an ink jet head

The structure of a seal for sealing the actuator cavity of an actuator according to the present invention is described below with reference to Fig. 7, Fig. 10, and Fig. 11.

As described above, the actuator cavity or the gap between the opposing electrodes of the actuator is preferably sealed while the HMDS concentration is high. It is therefore preferable to use a process in which the actuator cavity is sealed inside processing chamber for the HMDS deposition, but this process is accompanied by the following problems. Specifically, sealing the actuator cavity opening using a sealant, and particularly using an epoxy adhesive, inside the HMDS deposition processing chamber is not an easy task. In addition, contamination of the processing chamber with non-HMDS components from the adhesive is not desirable because of quality control problems.

It therefore follows that removing the electrostatic actuator (in the embodiment described above: the ink jet head) after exposure to HMDS in the processing chamber for a specific period, and then quickly sealing the actuator cavity immediately after removal, is better suited to mass manufacturing electrostatic actuators.

As previously described with reference to Fig. 7, the HMDS concentration in the actuator cavity drops immediately after removal from the processing chamber, and the durability drops if there is much of a delay between removal and sealing the actuator cavity. Referring again to Fig. 7, the slope of the curve in period A represents the rate of the drop in HMDS concentration in the actuator cavity after the electrostatic actuator is removed from the processing chamber. The faster this rate, that is, the steeper the slope of this curve, the sooner the actuator cavity must be sealed.

The present embodiment relates to a structure for sealing the actuator cavity, and relates particularly to a structure for suppressing the drop in HMDS concentration in the actuator cavity in the period between removal from the chamber and sealing.

Fig. 10 is a plan view of the seal area of an actuator cavity of the ink jet head shown in Fig. 1. As shown in

Fig. 10, segment electrode 18 and terminal portion 19 are connected by an interconnect 17b. Segment electrode 18 and interconnect 17b are formed by vapor deposition of ITO in recess 16 of glass substrate 4.

As shown in Fig. 10, recess 16 is separated into two parts. The part that becomes (when glass substrate 4 has been bonded to intermediate plate 3) the actuator cavity 15 has a width b and a length a, while the other part that becomes a connection tube or channel 15b, which links actuator cavity 15 to the outside of the ink jet head, has a width d and a length L. After HMDS is deposited inside actuator cavity 15, the open end of connection tube 15b is closed by sealant 20.

If V is the volume of actuator cavity 15 ($V = a \cdot b \cdot g$, where g is the gap length (the distance between diaphragm 5 and segment electrode 18)), and S is the cross sectional area of connection tube 15b ($S = d \cdot g$), the magnitude of a value K expressed by the following equation

$$K = V \cdot L/S$$

is related to the speed of the drop in the HMDS concentration in the actuator cavity 15 after removal from the HMDS deposition processing chamber. It was experimentally conformed that sufficient durability of the HMDS films can be assured in the electrostatic actuator even when the actuator cavity is sealed outside the processing chamber if $K \geq 25$.

Referring again to Fig. 7, the relationship between the durability and the time until the actuator cavity is sealed in period A is shown for the two cases of K = 10 and K = 25 by the solid line segment and the dotted line segment, respectively. As will be seen from the figure, a durability sufficient to withstand approximately 100 million deflection cycles or pulses can be achieved if the actuator cavity is sealed within the first minute after removal from the processing chamber when K = 25, but when K = 10, it is difficult to achieve even a durability of 10 million deflection cycles. Furthermore, the actuator cavity must be sealed within approximately 10 seconds after removal from the processing chamber if a durability of 100 million deflection cycles is to be achieved when K = 10, a requirement which is incompatible with and substantially impossible to achieve in a mass production environment.

Fig. 11 is a plan view of a seal area of an actuator cavity of an electrostatic actuator according to an alternative embodiment of the present invention. Note that like parts in Fig. 11 and Fig. 10 are identified by like numerals.

Each of a plurality of actuator cavities 15 arranged in series comprises a connection tube 15b connecting a respective actuator cavity 15 to a seal 20a, and a bypass tube or channel 15c connecting all of the connection tubes 15b to each other. A seal 20b is provided at the open end of this bypass tube 15c.

An ink jet head comprising electrostatic actuators according to the present embodiment of the invention is manufactured with HMDS sealed in actuator chambers 15 by means of the following process.

First, recesses are formed at specified locations in glass substrate 4 by etching, and electrode part 17 is formed at a specified location inside the recesses. This glass substrate 4 and intermediate plate 3 with diaphragms 5 are then anodically bonded together to form actuator cavities 15 and tubes 15b and 15c. After sealing the open end of each connection tube 15b with seal 20a, the ink jet head is placed in a chamber filled with a specific concentration of HMDS, and is left in this environment for a specified period of time. The ink jet head is then removed from the chamber, and the open end of bypass tube 15c is sealed with seal 20b to cut off the actuator cavities 15 from the outside air with HMDS sealed therein at a specified minimum concentration or greater.

Thus providing a bypass tube 15c makes it possible to increase the K value 50 to 60 times compared with a device in which no bypass tube 15c is disposed without increasing the area of the actuator or the ink jet head itself. In other words, the drop in HMDS concentration in the actuator cavity (the gap between the opposing electrodes of the electrostatic actuator) after removal from the processing chamber can be suppressed.

This method offers the additional advantage of enabling sealing to be completed more quickly because the actuator cavity of all actuators can be sealed at a single location after the HMDS deposition process, and the area to be sealed is smaller than the area that must be sealed when no bypass tube is provided.

Other embodiments

In the embodiments described above, the hydrophobic film is formed after the intermediate plate and the glass substrate 4 have been bonded together causing the hydrophobic film to be deposited on both of the opposing surfaces. The desired effect, namely to prevent the opposing surfaces from sticking together, may also be achieved with a hydrophobic film on only one of the two opposing surfaces. As will be appreciated by those skilled in the art, forming of a hydrophobic film on only one of the opposing surfaces may easily be achieved when the deposition step precedes the bonding step and only one of the surfaces is exposed to the deposition step.

Furthermore, HMDS has been described above as the material for the hydrophobic film. In fact, HMDS is only one member of a class of materials that may be used in accordance with the present invention. The class may be generally defined as an organosilicate compound having a hydrophobic functional group and the ability to react with a hydroxyl group. Particularly preferable materials of this class are compounds having the functional group R_3-Si-X wherein R represents an alkyl group and X represents either a halogen or an

amino group or silylated amine, such as hexamethyldisilazane ($(CH_3)_3SiNHSi(C_2H_5)_3$) (HMDS), hexaethyldisilazane ($(C_2H_5)_3SiNHSi(C_2H_5)_3$), trimethylchlorosilane ($(CH_3)_3SiCl$), triethylchlorosilane ($(C_2H_5)_3SiCl$), trimethylaminosilane ($(CH_3)_3SiNH_2$) and triethylaminosilane ($(C_2H_5)_3SiNH_2$). Experiments showed that what has been discussed above with reference to HMDS applies to these other materials in substantially the same way.

It will be understood by those skilled in the art that while ink jet head 1 has been described above as a face nozzle type ink jet head in which ink drops are ejected from ink nozzles disposed on the surface of a substrate, the present invention can also be applied to edge nozzle ink jet heads in which ink drops are ejected from ink nozzles disposed along an edge of the substrate.

Furthermore, while the present invention has been described as applied to an ink jet head, use of an electrostatic actuator in accordance with the invention is not limited to ink jet heads. Examples of other applications include micromechanical devices such as disclosed in JP-A-7-54259, display apparatuses using electrostatic actuators, and micropumps.

Effects of the invention

As described above, an electrostatic actuator according to the present invention comprises a hydrophobic film of a material such as hexamethyldisilazane (HMDS) formed on opposing surfaces of opposing electrode members adapted to be displaced relative to each other by electrostatic force. The molecules of such hydrophobic films are smaller than those of PFDA, and the durability and film stability of the hydrophobic films are substantially improved by sealing the space including the hydrophobic film(s) airtight. It is therefore possible by means of the present invention to form a uniform hydrophobic film substantially free of variations in an electrostatic actuator having a narrow gap between opposing electrode members. In addition, an electrostatic actuator with high durability and operating stability can be achieved.

A manufacturing method for an electrostatic actuator according to the present invention forms an airtight seal to a cavity formed by or including the gap between those opposing electrode members while the concentration of the material for the hydrophobic film in that cavity is above a specified level after forming the film on the surfaces of the opposing electrode members, which face each other. As a result, a hydrophobic film with outstanding durability can be achieved in a short period of time. Furthermore, durability can also be improved even when the cavity is sealed after air exposure for a specific period of time after hydrophobic film formation.

Claims

1. An electrostatic actuator having

   a first and a second electrode member (5, 18) opposing each other via a gap and being displaceable relative to each other,

   drive means (5, 18, 25) for displacing said first and second electrode members relatively to one another by creating an electrostatic force between said first and second electrode members, and

   a hydrophobic film (22, 23) formed on at least one of the two opposing surfaces of said first and second electrode members,

   wherein the hydrophobic film is formed from an organosilicate compound having a hydrophobic functional group and the ability to react with a hydroxyl group, and the gap between said first and second electrode members (5, 18) is sealed airtight.

2. The actuator according to claim 1, wherein said compound has the general formula R_3SiX, wherein R represents an alkyl group and X represents either a halogen or an amino group or silylated amine.

3. The actuator according to claim 2, wherein said compound is selected from a group of compounds including hexamethyldisilazane ($(CH_3)_3SiNHSi(C_2H_5)_3$), hexaethyldisilazane ($(C_2H_5)_3SiNHSi(C_2H_5)_3$), trimethylchlorosilane ($(CH_3)_3SiCl$), triethylchlorosilane ($(C_2H_5)_3SiCl$), trimethylaminosilane ($(CH_3)_3SiNH_2$) and triethylaminosilane ($(C_2H_5)_3SiNH_2$).

4. The actuator according to claim 3, wherein said compound is hexamethyldisilazane and the hexamethyldisilazane concentration between said first and second electrode members (6, 19) is 0.4% or greater.

5. The actuator according to claim 3, wherein said compound is hexamethyldisilazane and the hexamethyldisilazane concentration between said first and second electrode members (6, 19) is 0.9% or greater.

6. The actuator according to any one of the preceding claims, further comprising:

   a tube (17b) communicating with said gap between said first and second electrode members (6, 19) , and

   a sealing member (20) for sealing said tube and thereby isolating said gap from the atmosphere surrounding the actuator,

   wherein the relationship between the volume V of the gap, and the cross sectional area S and the length L of said tube (17b) satisfy the condition $V \cdot L/S \geq 25$.

7. Use of the actuator according to any one of the preceding claims with an ink jet head, comprising

an ink chamber (7) arranged such that its volume changes in response to said relative displacement of said first and second electrode members (6, 19) of the actuator, and
a nozzle (21) communicating with said ink chamber (7),

wherein said drive means comprises a respective electrode (6, 19) formed on or by each of said opposing electrode members, and means (25) for applying an electrical pulse voltage across said electrodes,

such that an ink drop is ejected from said ink nozzle in response to said electrical pulse voltage.

8. A method of manufacturing an electrostatic actuator as defined in claim 1, 2 or 3, comprising steps of:

(a) depositing a hydrophobic film (22, 23) of said compound on one or both opposing surfaces of said first and second electrode members (6, 19), and
(b) sealing airtight the gap between the opposing surfaces of said first and second electrode members so that said hydrophobic film (22, 23) is deposited stably on said one or both opposing surfaces.

9. The method according to claim 8, wherein step (b) comprises:

using hexamethyldisilazane as said compound and performing said sealing while the hexamethyldisilazane concentration in the gap has a specified value.

10. The method according to claim 9, wherein said specified value is 0.4% or greater.

11. The method according to claim 9, wherein said specified value is 0.9% or greater.

12. The method according to any one of claims 9 to 11, wherein step (b) is performed at room temperature and atmospheric pressure.

13. The method according to any one of claims 9 to 11, wherein

step (a) comprises depositing said hydrophobic film (22, 23) by exposing said first and second electrode members (6, 19) to a gasified atmosphere of said compound at atmospheric pressure, and
step (b) is performed in the deposition atmosphere.

14. The method according to any one of claims claim 8 to 13, further comprising a step of

(c) post-processing for stabilizing said hydrophobic film (22, 23) formed in step (a), comprising:

(c1) imparting moisture to said hydrophobic film, and/or
(c2) exposing said hydrophobic film for a specific period of time to air at a predetermined temperature and predetermined humidity.

15. The method according to claim 14, wherein the step (c1) begins before step (a) ends.

16. The method according to any one of claims 8 to 15, further comprising

(d) a pretreatment step to reduce moisture between said opposing surfaces, step (d) being performed prior to step (a).

17. The method according to claim 16, wherein step (d) comprises heating in a vacuum.

18. The method according to claim 16, wherein step (d) comprises alternating the atmosphere to which said opposing surfaces are exposed between a vacuum atmosphere and a nitrogen atmosphere.

19. The method according to claim 16, wherein the step (d) comprises placing the electrostatic actuator in a chamber, and supplying a stream of dry gas to the chamber for a specified period of time.

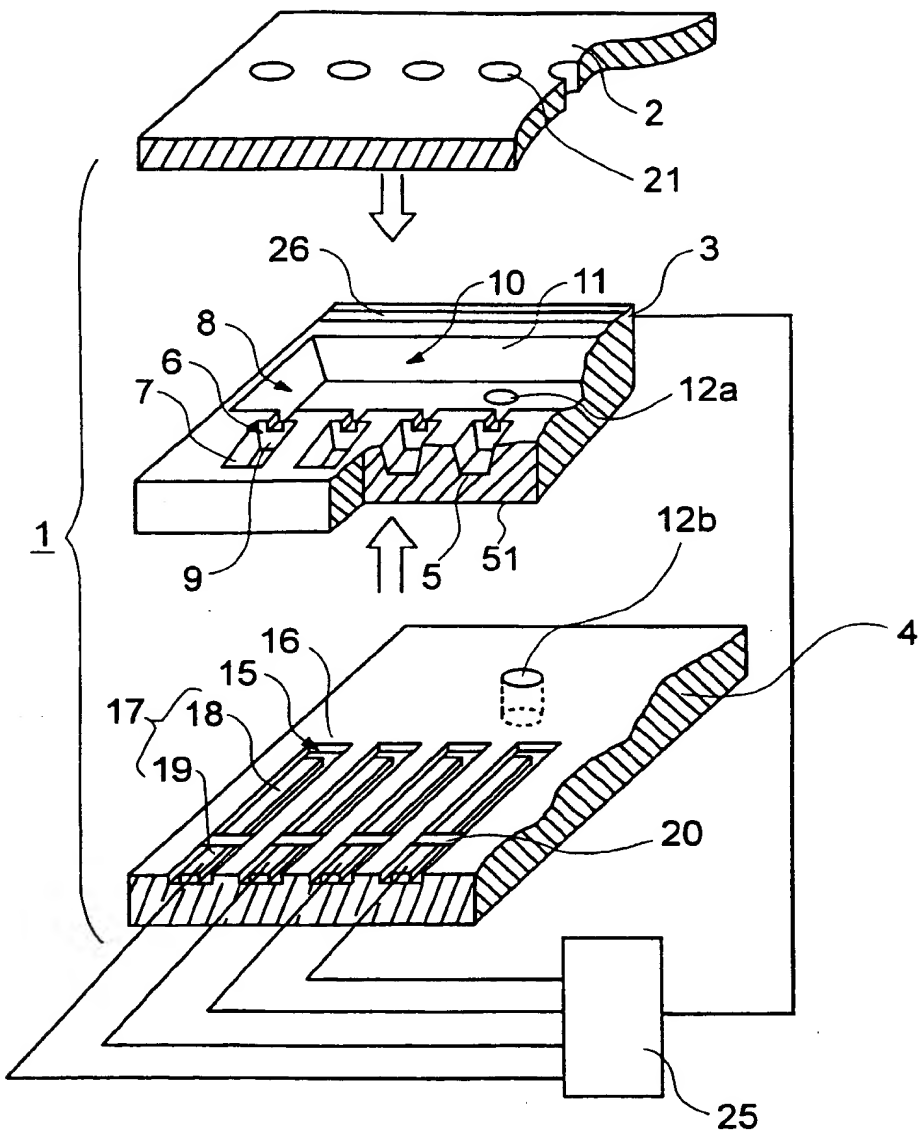

FIG. 1

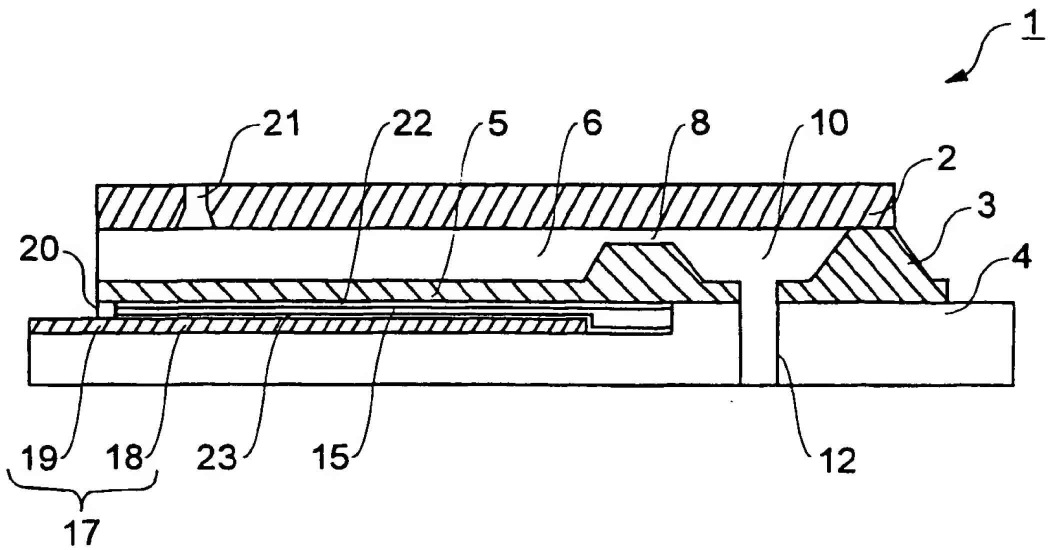

FIG. 2

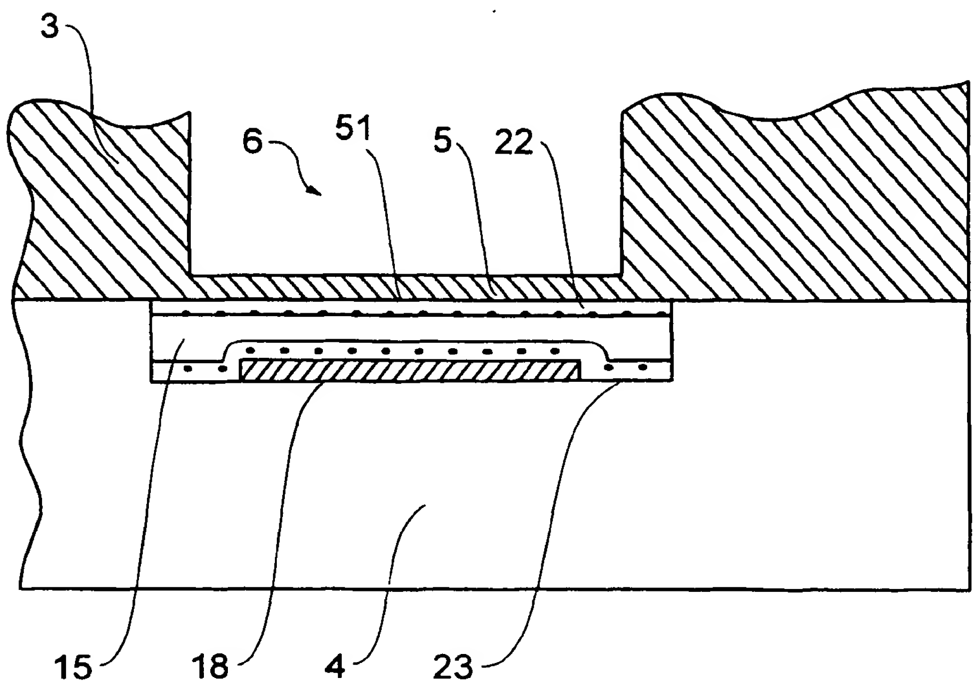

FIG. 4

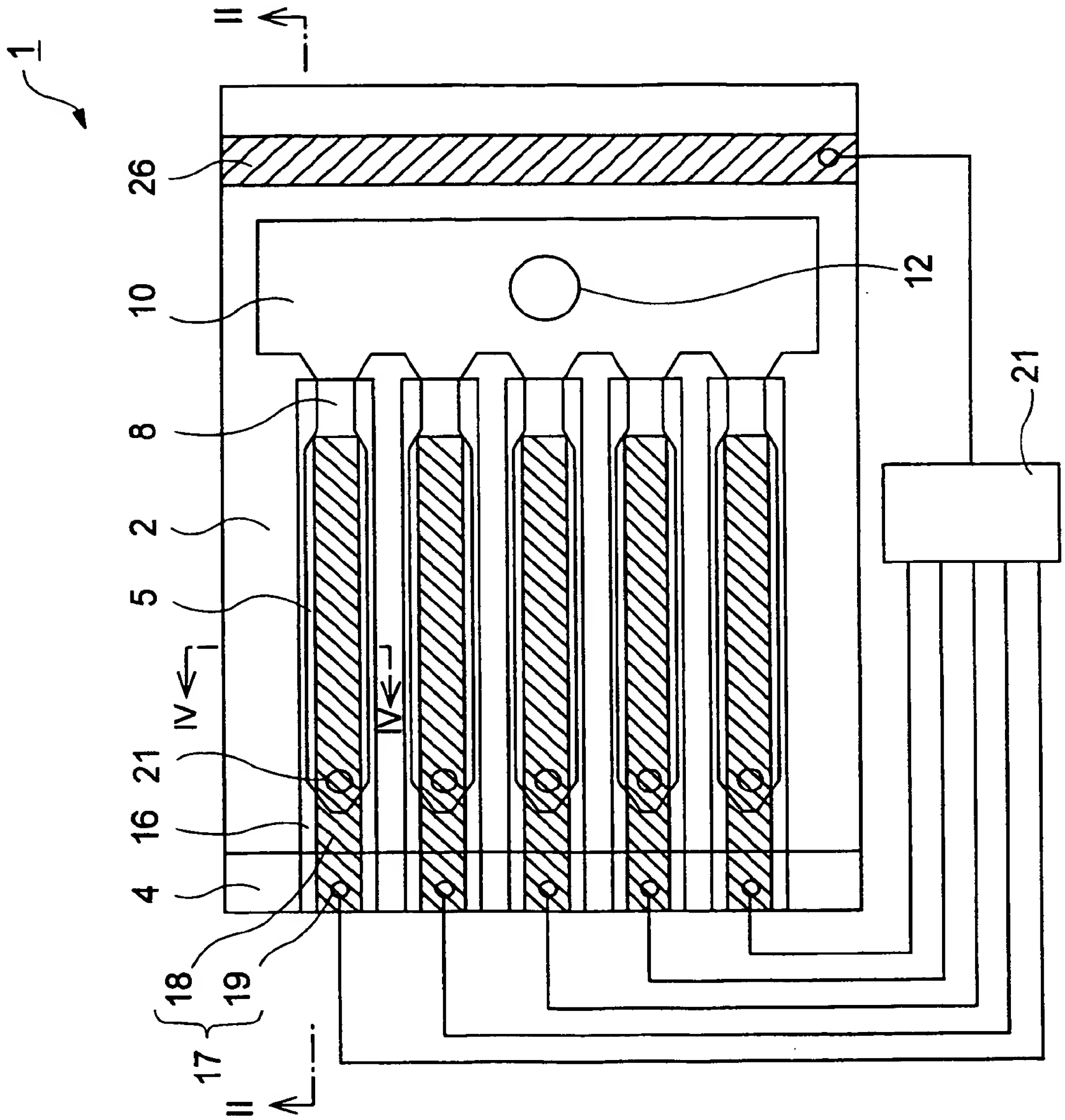

FIG. 3

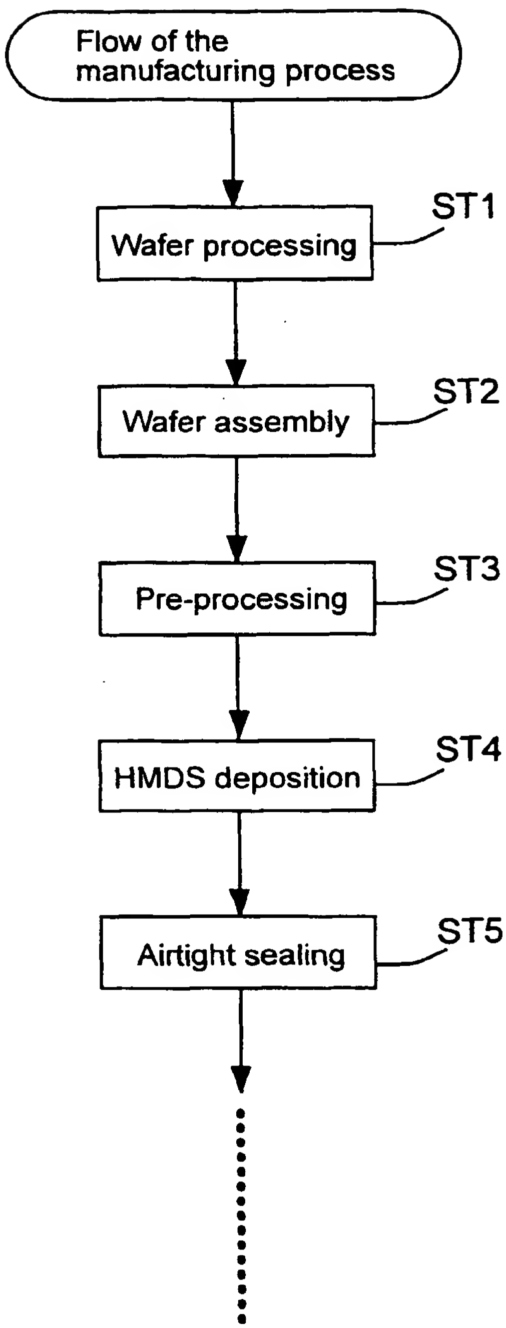
Flow of the manufacturing process
Wafer processing
ST1
Wafer assembly
ST2
Pre-processing
ST3
HMDS deposition
ST4
Airtight sealing
ST5

FIG. 5

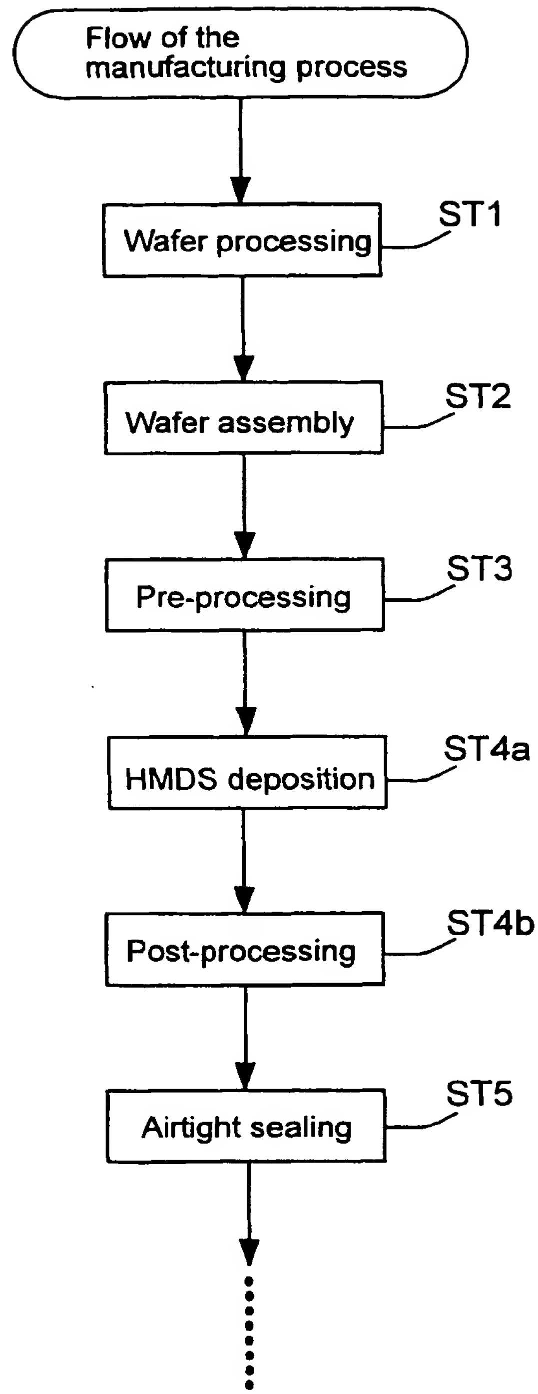
Flow of the manufacturing process
Wafer processing
ST1
Wafer assembly
ST2
Pre-processing
ST3
HMDS deposition
ST4a
Post-processing
ST4b
Airtight sealing
ST5

FIG. 9

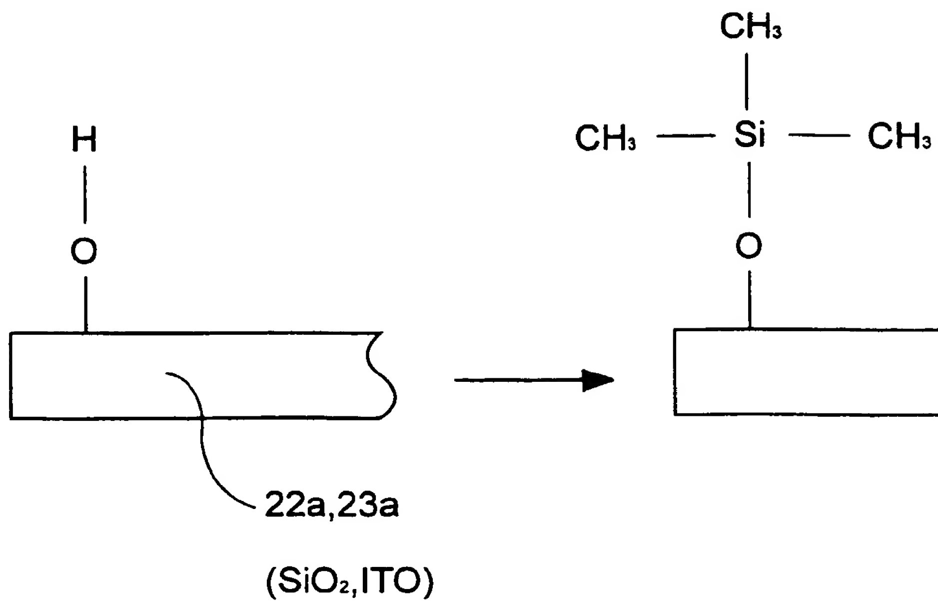

FIG. 6

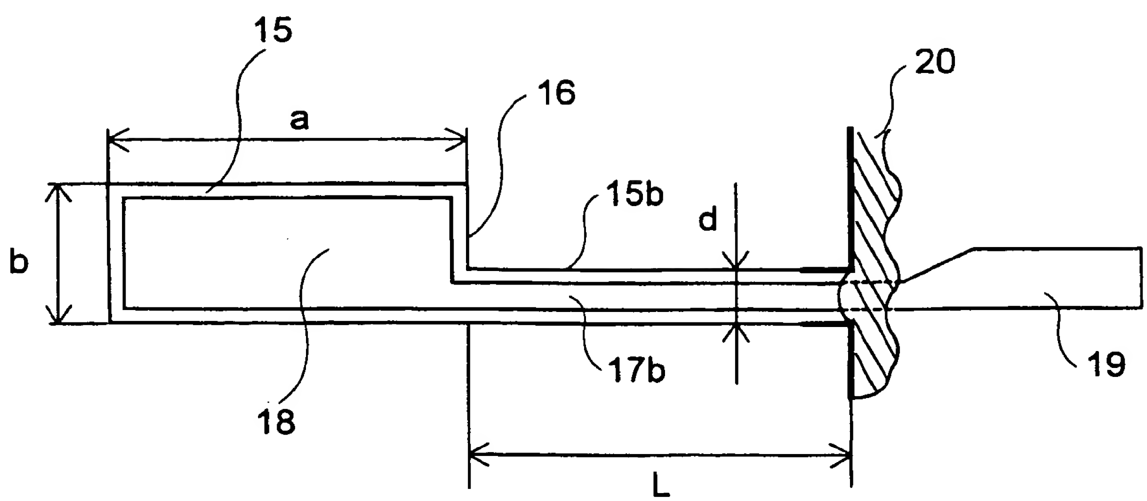

FIG. 10

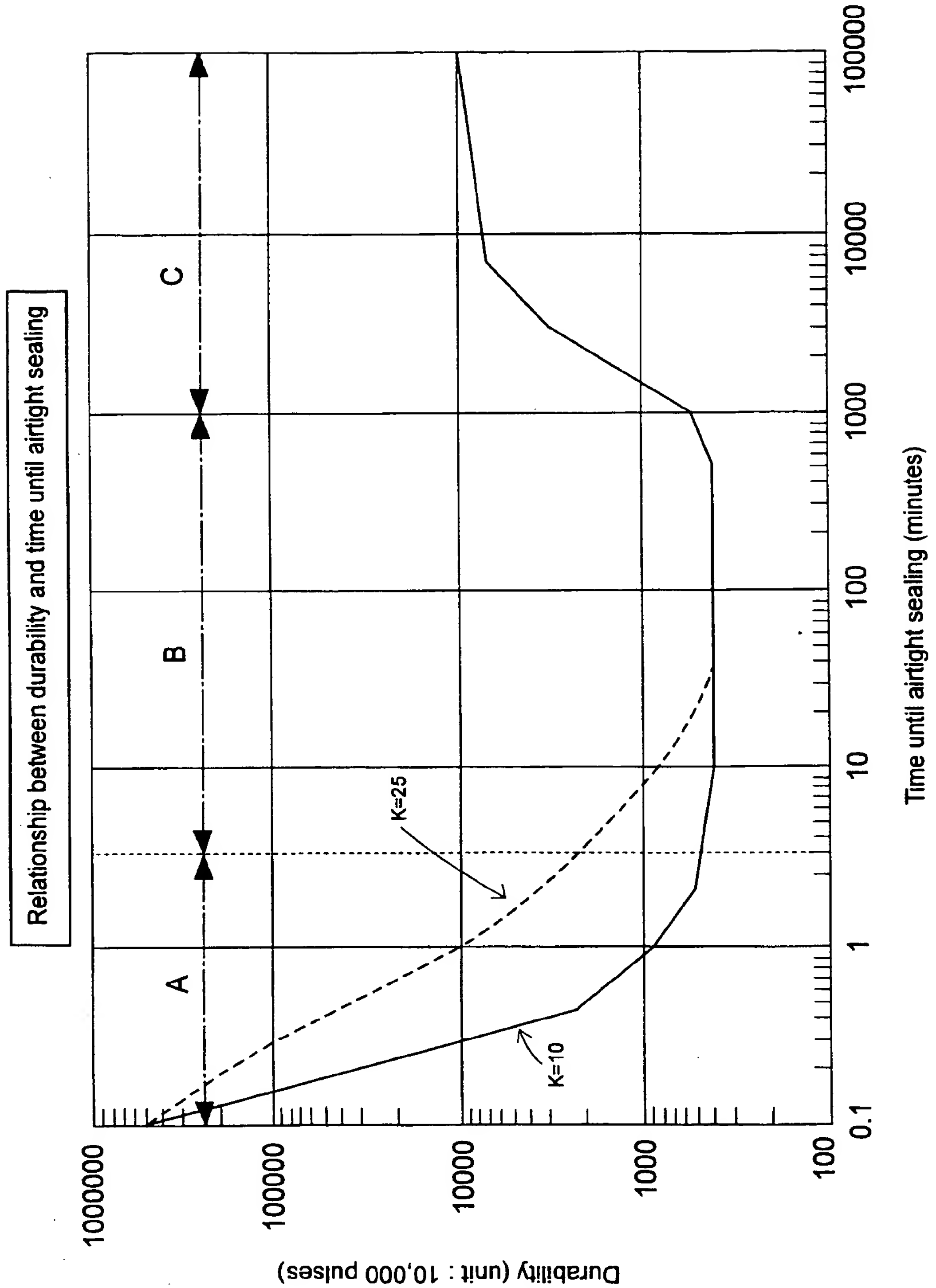
Relationship between durability and time until airtight sealing
A
B
C
K=25
K=10
Durability (unit : 10,000 pulses)
1000000
100000
10000
1000
100
Time until airtight sealing (minutes)
0.1
1
10
100
1000
10000
100000

FIG. 7

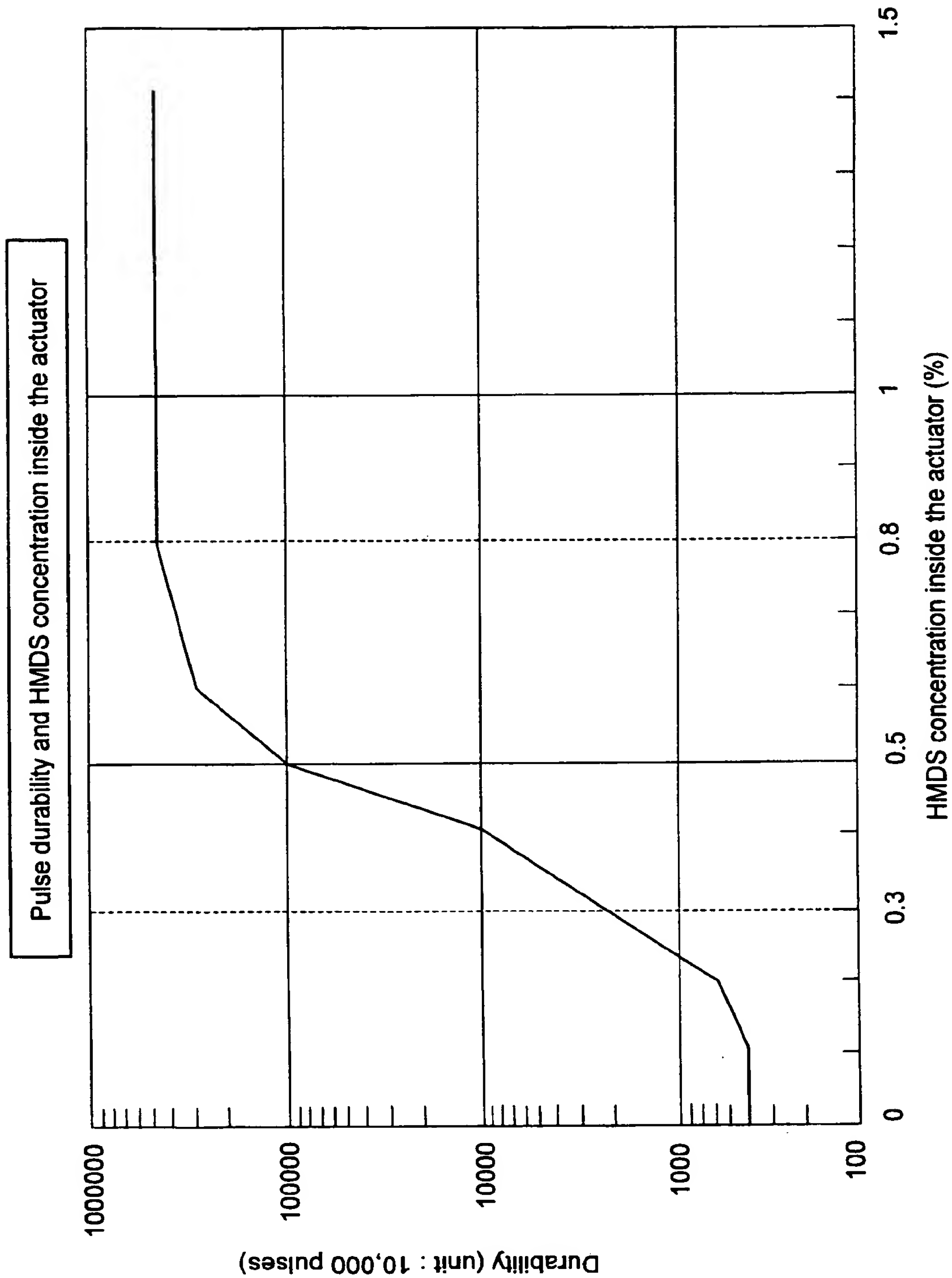
Pulse durability and HMDS concentration inside the actuator
Durability (unit : 10,000 pulses)
1000000
100000
10000
1000
100
0
0.3
0.5
0.8
1
1.5
HMDS concentration inside the actuator (%)

FIG. 8

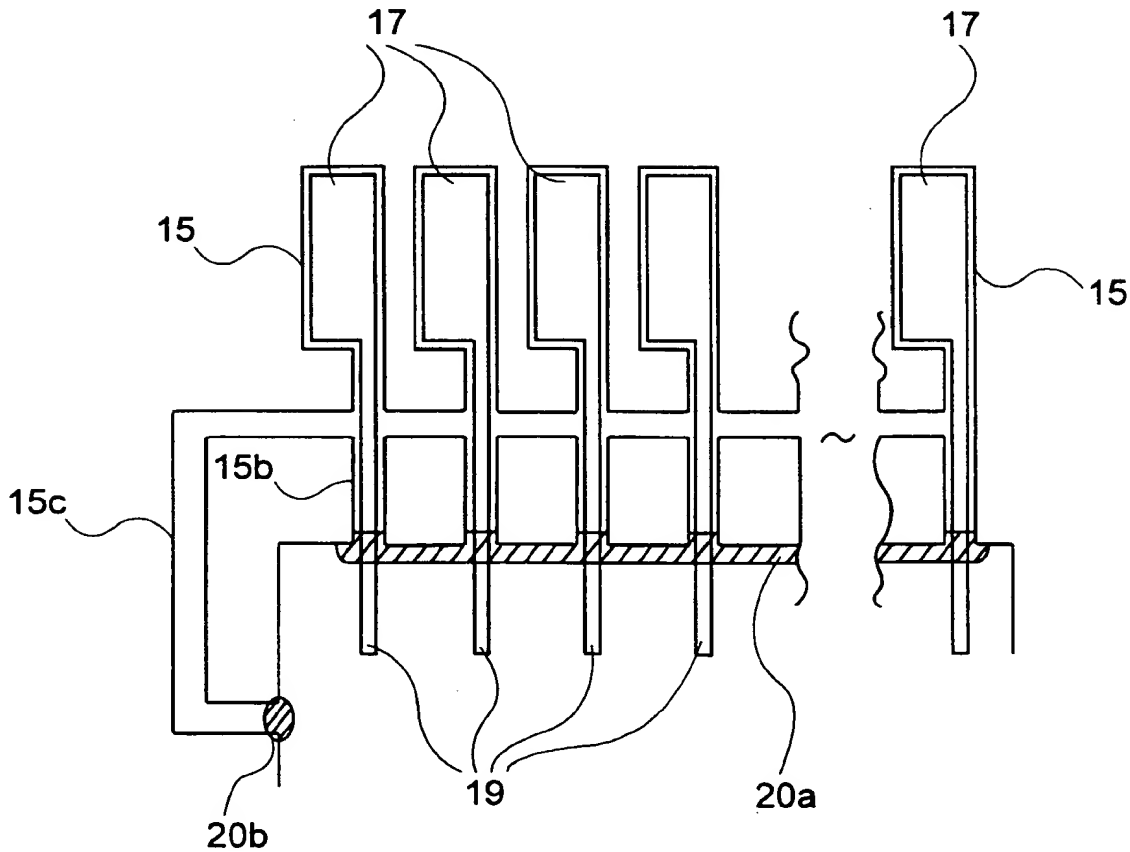

FIG. 11

(19) Europäisches Patentamt
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Office européen des brevets

(11) EP 0 849 082 A3

(12) **EUROPEAN PATENT APPLICATION**

(88) Date of publication A3:
14.04.1999 Bulletin 1999/15

(43) Date of publication A2:
24.06.1998 Bulletin 1998/26

(21) Application number: **97122537.0**

(22) Date of filing: **19.12.1997**

(51) Int. Cl.[6]: **B41J 2/06**, B41J 2/14, B41J 2/16

(84) Designated Contracting States:
AT BE CH DE DK ES FI FR GB GR IE IT LI LU MC NL PT SE
Designated Extension States:
AL LT LV MK RO SI

(30) Priority: **20.12.1996 JP 342213/96**
16.10.1997 JP 284127/97

(71) Applicant:
SEIKO EPSON CORPORATION
Tokyo 163 (JP)

(72) Inventors:
- **Sato, Kazuhiko**
  Suwa-shi, Nagano-ken 392 (JP)
- **Maruyama, Hiroyuki**
  Suwa-shi, Nagano-ken 392 (JP)
- **Fujii, Masahiro**
  Suwa-shi, Nagano-ken 392 (JP)
- **Hagata, Tadaaki**
  Suwa-shi, Nagano-ken 392 (JP)
- **Kitahara, Koji**
  Suwa-shi, Nagano-ken 392 (JP)
- **Mukaiyama, Keiichi**
  Suwa-shi, Nagano-ken 392 (JP)

(74) Representative:
Hoffmann, Eckart, Dipl.-Ing.
Patentanwalt,
Bahnhofstrasse 103
82166 Gräfelfing (DE)

(54) **Electrostatic actuator and method of manufacturing it**

(57) An electrostatic actuator comprising opposing electrode members displaced relatively by an electrostatic force is provided with improved durability so that electrostatic attraction between the opposing electrode members does not drop and the opposing electrode members do not stick together. Hydrophobic films (22) and (23) of hexamethyldisilazane (HMDS) are formed on the surface of a segment electrode (19) and the bottom surface of a diaphragm (common electrode) (6) of electrostatic actuator wherein the diaphragm forms a wall of an ink chamber 7 in a ink jet head 1. HMDS molecules are smaller than PFDA molecules, and a uniform, variation-free hydrophobic film can therefore be formed even when the gap between the two electrodes is narrow. Durability and film stability of hydrophobic films are also high. An electrostatic actuator with high durability and operating stability can thus be achieved.

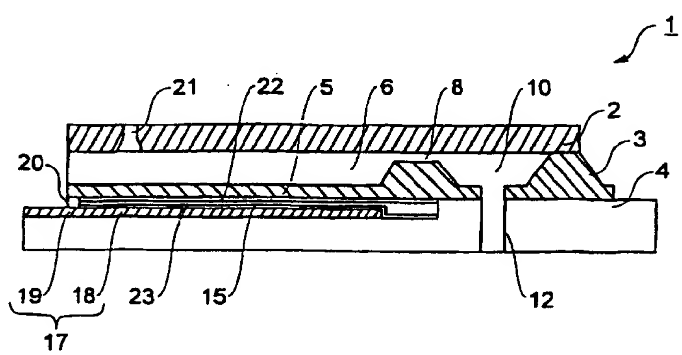

FIG. 2

EP 0 849 082 A3

European Patent Office

EUROPEAN SEARCH REPORT

Application Number
EP 97 12 2537

DOCUMENTS CONSIDERED TO BE RELEVANT

Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (Int.Cl.6)
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A	WO 93 14422 A (STIMSONITE CORP) 22 July 1993 * page 5, line 27 * ---	1	TECHNICAL FIELDS SEARCHED (Int.Cl.6)
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The present search report has been drawn up for all claims

Place of search	Date of completion of the search	Examiner
THE HAGUE	19 February 1999	Bardet, M

CATEGORY OF CITED DOCUMENTS

X : particularly relevant if taken alone
Y : particularly relevant if combined with another document of the same category
A : technological background
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T : theory or principle underlying the invention
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For more details about this annex : see Official Journal of the European Patent Office, No. 12/82